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# Water retention and drainage on air side of heat exchangers—A review

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This paper presents the recent advances in water retention and drainage performance on air side of heat exchangers under wet and dehumidifying conditions. The experimental and numerical research results are addressed. The water retention and drainage characteristics of the widely-used heat exchangers (fin-and-tube type and flat-tube type), the effects of heat exchanger surface materials, long term dry/wet cycles and liquid droplet shape on performance are highlighted. The current research results on modeling of water retention and drainage on heat exchangers are summarized.



**Contents**



## 1. Introduction

In air conditioning and refrigeration systems, heat exchangers are usually operated below the dew point temperature of the moist air. Water vapor in air will condense and accumulate on heat exchanger surface. The water condensate retention and drainage behaviors are dominated by the forces acting on their bodies including the surface tension, flow drag caused by air velocity and gravity. Some of these forces help the water from flowing out and others keep the water retained on heat exchanger surfaces. Water retention will not only affect the thermal–hydraulic performance of heat exchangers, but also influence the supplied air quality and compartment comfort. The wet surface is a good medium for biological activities that could lead to odors and health problems.

Retained condensate profoundly affects the heat exchanger performance when it covers on heat exchanger surfaces. There are numerous studies of the effect of water retention on the thermal–hydraulic performance of variable heat exchangers under

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wet or dehumidifying conditions [1–14]. Although sometimes the heat exchanger surface is partially wet, most investigations only consider that the surface is fully wet or fully dry under wet conditions. The water retention on the heat exchanger surfaces has hydrodynamic effects by changing the surface geometry and flow pattern. Water condensate adhering on surfaces will block the air flow path to increase the air-side frictional pressure drop. Depending on air side condition, heat exchanger type and geometry, retained water can decrease [1] or increase [5] air side heat transfer coefficient. Wang and Chang's [1] experimental results showed that the hydrophilic coating and inlet relative humidity have no influence on the sensible heat transfer coefficient under wet test conditions, but air side pressure drop is sensitive to the inlet relative humidity. From the previous researches [2,3], it can be concluded that there is a performance transition from enhancement to degradation for aluminum plate fin occurring at a fixed fin pitch. But this phenomenon does not appear at interrupted fin such as louver fin. Wang et al. [4] also tested the louver-fin-and-tube heat exchangers under wet conditions. The results showed the similar trend and conclusions with the former tests. McLaughlin and Webb [5] experimentally studied the performance of automotive evaporators with flat tubes and louver fins under wet conditions. The results revealed that a critical louver pitch makes the wet sensible heat transfer coefficient reduce dramatically. They also implied that the hydrophilic coating surface increased air side heat transfer coefficient by 25% over an uncoated evaporator which is different from the experimental conclusion in fin-and-tube heat exchangers [1]. There are tons of heat transfer and friction factor correlations under wet conditions in literatures for different types of fins and heat exchanger geometries. More information can be obtained from Refs. [15,16].

The main objective of the present review is to highlight the recent advances on experimental and numerical studies of water retention and drainage on air side of heat exchangers widely used in air conditioning and refrigeration systems and chemical engineering including tube-and-fin and compact flat tube heat exchangers. The effects of heat exchanger surface materials, long-term dry/wet cycles and liquid droplet shapes on performance will be critically reviewed. The main experimental methods will also be introduced. The mathematical models and CFD studies of water retention and drainage behaviors on tube-and-fin and flat-tube type heat exchangers will be described in the last section.

## 2. Experimental researches

### 2.1. Fin-and-tube heat exchangers

Condensate retention on fin-and-tube heat exchangers were investigated from the real-time and steady-state experiments by Korte and Jacobi [17] in wind tunnel equipment. The test results showed that the quantity of retained condensate will be stable when condensate deposition and shedding attain balance. The similar water retentions were observed on the heat exchanger surfaces which had the same surface wettability and geometry. Air flow force did not have significant influence on condensate retention for heat exchangers with large fin spacing (12 FPI) or with hydrophilic coatings under a wide range of air velocity (1.5–8 m/s). Although many interesting results were concluded in these studies, the heat exchanger types, fin geometry, fin materials and fin spacing were limited.

When water retention on heat exchanger surface was not removed on time, the water may be sprayed out of heat exchanger surface under the force of flow drag. Min and Webb [18] conducted an experimental study to investigate the condensate carryover phenomena in dehumidifying heat exchangers. Two wavy

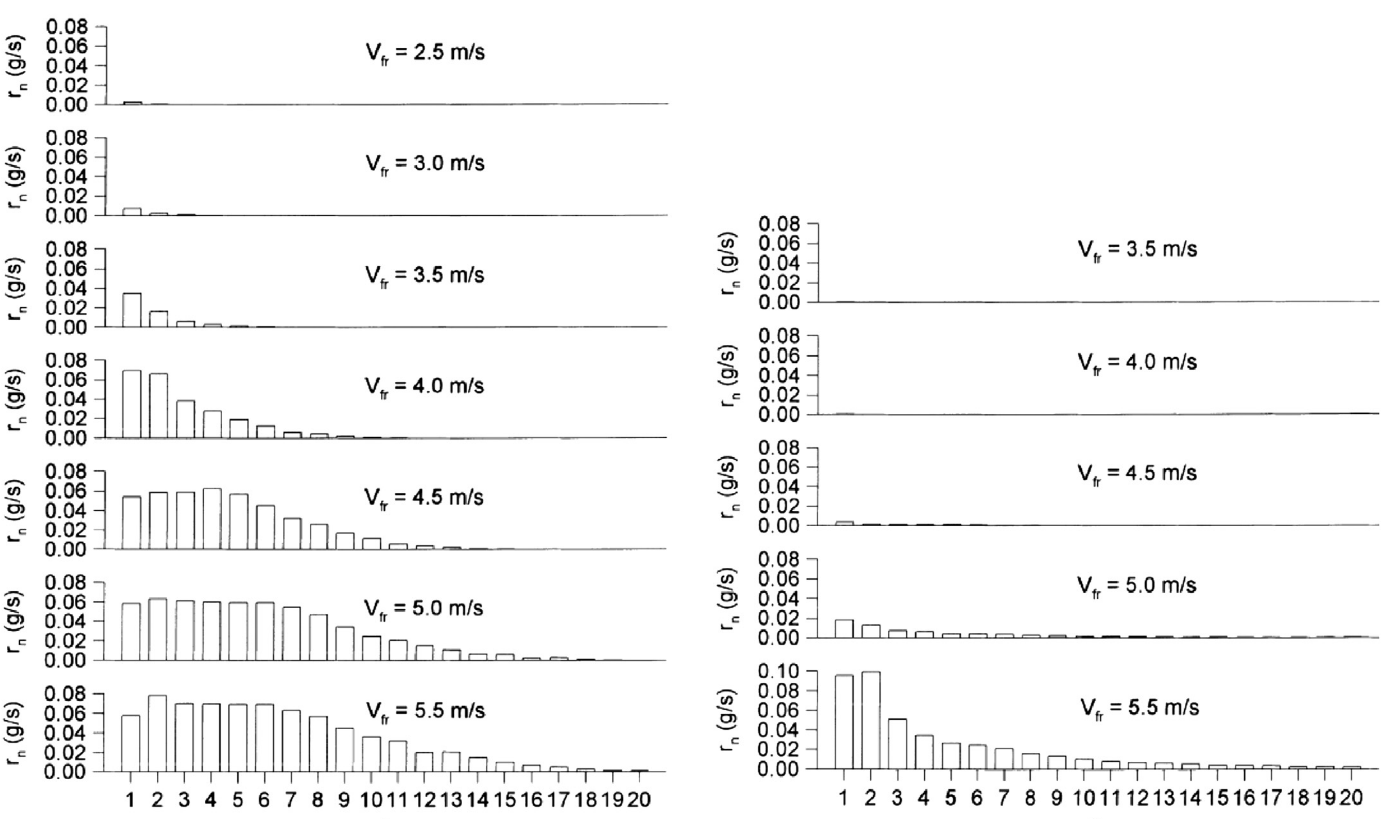


**Fig. 1.** Condensate carryover characteristics for two coils [18]. (a) New coil ($\theta_R$=70°) and (b) coil having experienced 100 cycles ($\theta_R$=10°).

finned-tube coils were tested with special treatment fins whose contact angles were 70° and 10°. They concluded that air face velocity and receding contact angle played the key roles in the condensate carryover and condensate retention mass as shown in Fig. 1. The experimental results showed that the quantity of condensate carryover increased with the increasing frontal velocity. The coil having a 10° receding contact angle could retain dramatically less condensate carryover than the coil having a 70° receding contact angle. Also the receding contact angle obviously affected the condensate droplets and bridges formation as shown in Fig. 2. There were more condensate droplets and bridges observed on the fin surfaces of the 70° receding contact angle coil than those observed on the fin surfaces of the 10° receding contact angle coil. And the dominant carryover was contributed to the condensate "bridges" between the adjacent fin surfaces.

Yin and Jacobi [19] conducted an experimental study on the effect of condensation on air-side heat transfer performance for plain-fin-and-tube and wavy-louvered heat exchangers with variable fin spacing which was smaller than that in the previous studies [17]. In real-time retention tests, the mass of retained condensate in the plain-fin-and-tube heat exchangers increased until reaching a maximum. After reaching the maximum, the quantities of retained condensate dropped quickly and would maintain a steady value finally when the forces on droplets and condensate reach balance. The test results also showed that the fin density affected the total amount of condensate and the maximum behavior disappeared with a higher fin density. The stable retained condensate mass would increase and approached a maximum value. This phenomenon was also seen in the wavy-louvered heat exchangers tests. According to the test results, the retained condensate had little relationship with air flow velocities at a relative small velocity, but was dependent on fin geometry and contact angle. The photographs of wet surface showed that the percentage of heat transfer area covered by droplets was similar for the top and middle sections; however a big decrease of covered area was found for the bottom section. This could be attributed to sweeping effects where the bottom section would be affected by all the droplets that sweep from the above two sections.

Zhong et al. [20] designed a new quick and simple test method to assess the condensate drainage behavior of the air-side surface for compact heat exchangers-dynamic dip testing. More than 20 flat-tube and round-tube-and-fin heat exchangers were tested. In the comparison results, the round-tube-and-fin heat exchanger can remove condensate quicker than flat-tube louver fin heat exchanger and two different drainage patterns for both fin types is shown in Fig. 3.

Joardar et al. [21] experimentally studied the effect of heat exchanger orientation, surface coating and fin surface enhancement on off-cycle condensate drainage and retention using the dynamic dip testing method proposed by Zhong et al. [20]. The test results showed that for the flat-top wavy fin design with not any other passage for drainage, inclination could improve water drainage and reduce the final steady-state retention mass. The heat exchanger with hydrophilic surface retained less water mass compared to the hydrophobic surface. For the high fin density heat exchangers, inclination almost had no influence on drainage because surface tension force played a key role in the drainage process. For the single header heat exchanger, cutting out the bottom plate would gain about a 15% improvement in drainage. In order to improve drainage behavior, a new approach called "drainage enhancing strips (DES)" by which some strips will be sticked on the bottom to break surface tension and surface treatment was used to gain roughly a 20% improvement in

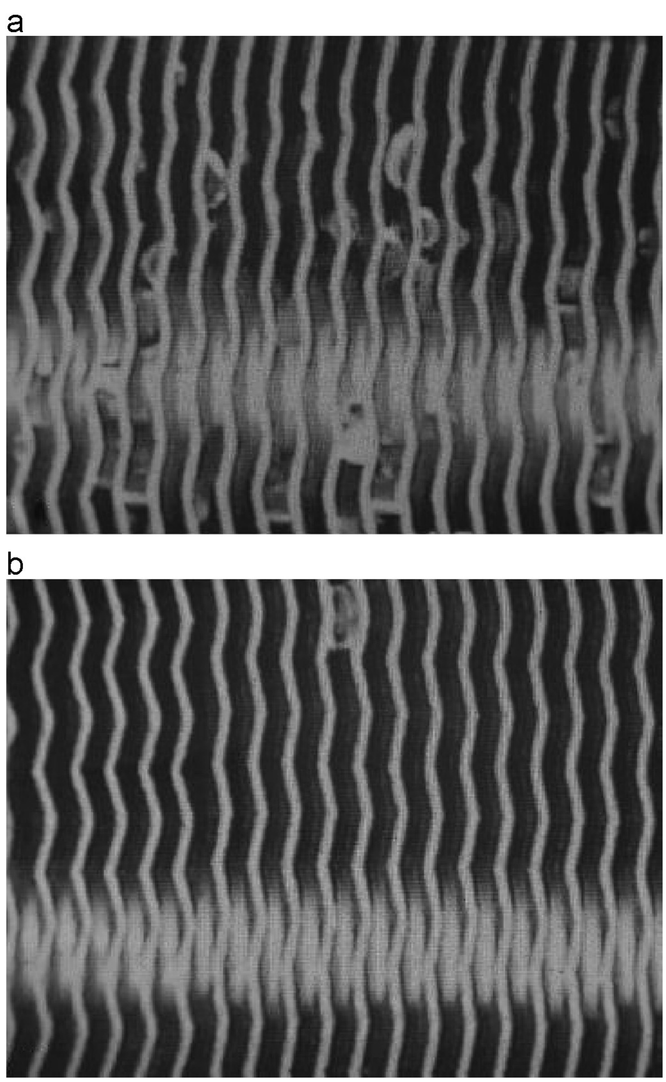


**Fig. 2.** Condensate water blocks the fin spacing at different surface contact angles (a, 70°; b, 10°) [18].

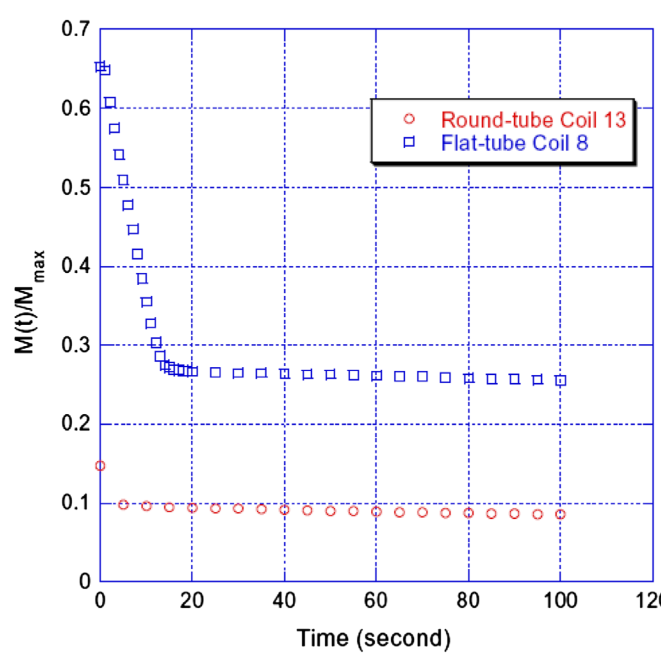


**Fig. 3.** Experiments to explore drainage patterns for flat-and-round-tube heat exchangers [20].

drainage performance of mobile laminated evaporator with louvered fin as shown in Fig. 4.

### 2.2. Flat-tube heat exchangers

Flat-tube heat exchangers are usually used in automobile air conditioning systems, such as laminated evaporators. In general, the tube is flat or plate, the fin is louvered. McLaughlin and Webb [23] experimentally studied the condensate formation on air-side surface of brazed aluminum, louver fin automotive evaporators. The results indicated that condensate could “bridge” the space between two adjacent fins or louvers and altered the air flow through the evaporator, causing a change in the heat transfer and friction characteristics as shown in Fig. 5. The qualitative observations of condensate draining were tested in a single column of louver fins brazed to a refrigerant tube using table-top wind tunnel facility, but the whole condensate mass measurements were performed by dip testing method. The test data revealed that the louver pitch was the most important parameter to determine the condensate drainage behavior and ability. For example, an evaporator with 1.1 mm louver pitch retained 26% more condensate than an evaporator with 1.3 mm louver pitch. The authors implied that more water “bridge” in smaller louver pitch evaporator and also pointed out that the intersection of a fin base and a channel would increase water retention on heat exchanger surface because of increase in fin bridging.

Kariser and Jacobi [24] experimentally studied the effect of condensate accumulation and shedding on the air-side thermal performance of automotive evaporator units. Condensate retention data were collected at both real-time and steady-state conditions to quantitatively determine how condensates load up on a coil surface. It was found that the heat transfer coefficient decreased and the pressure drop increased for all the test samples because the bridges formed in the inter-louver space and redirect the flow from the desired louver-directed flow to duct directed flow. The larger louver pitches could prevent louver bridging, but

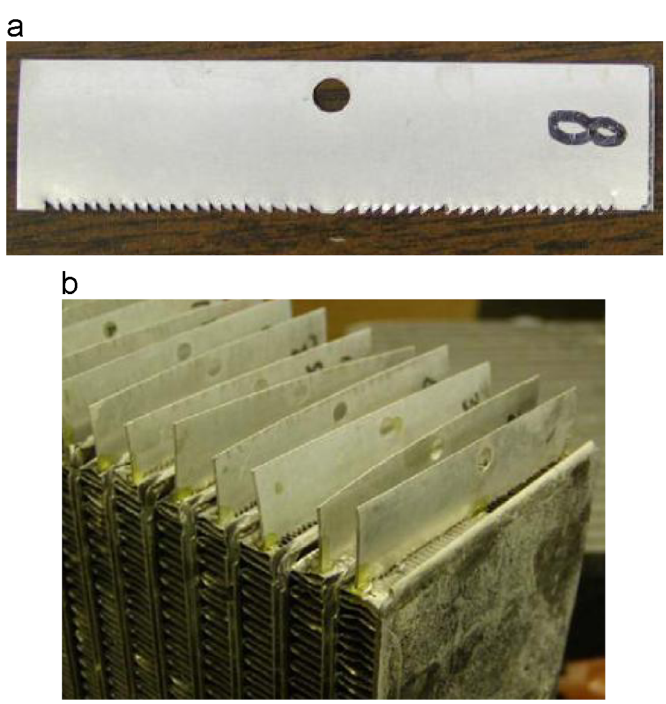

**Fig. 4.** DES method to improve condensate drainage [21]. (a) The aluminum saw tooth DES designed for enhanced contact with louver. (b) Picture shows the saw toothed DES mounted on the heat exchanger.

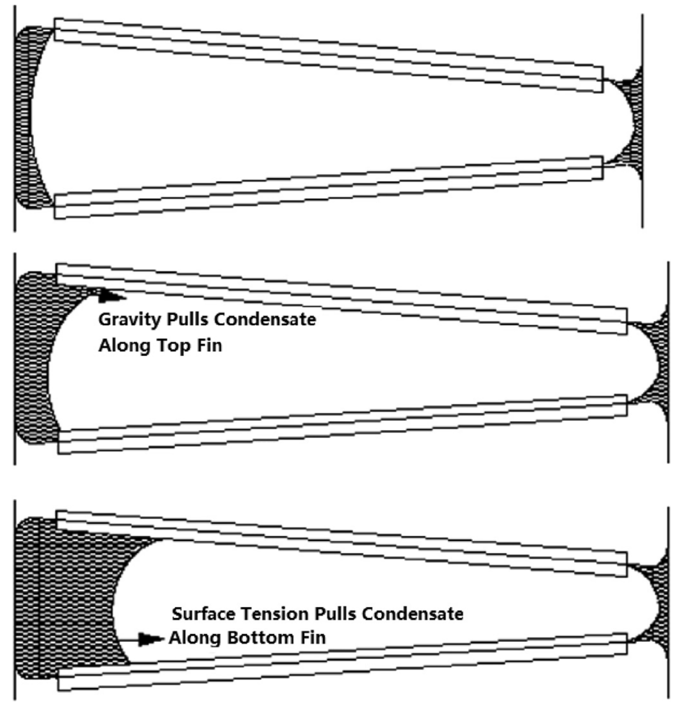


**Fig. 5.** (Top) Condensate menisci at the fin base and opening before bridging starts; (middle) gravity pulls condensate downward along topmost fin; and (bottom) surface tension pulls condensate along the bottom fin [23].

decreased absolute performance of the coil. In the drainage tests, two distinct drainage patterns were observed: the fast draining coils could reach a steady-state within about 2 minutes and the slow drainage coils could continue draining water for up to 4 hours. The authors also pointed out that when an inter-louver bridge existed, gravitational forces were not sufficient to remove the bridges.

Osada et al. [25] tested one single row of aluminum corrugated louver fin brazed with aluminum plates on both fin sides. The water condensate process was visualized and the effects of surface wettability, fin geometries and surface coating on water condensate were experimented. The test results showed that the surface with hydrophilic coating near fin outlet improved the fin heat transfer performance and drainage. They also concluded that some optimal fin design could promote the water drainage and the optimal installation position of evaporator under wet conditions was more than 30° inclination windward from the vertical direction.

Joardar et al. [26] introduced dynamic dip testing method to observe the condensate drainage behavior in compact heat exchanges under wet conditions. About 20 compact heat exchangers used in mobile AC system were tested and the real-time water retentions in heat exchangers were recorded. In the experiments, two distinct drainage patterns were observed mostly like the patterns of Kariser and Jacobi [24]. One existed in compact heat exchangers which make a rapid transition to the steady state after the free-fall regime. Another type showed a more gradual transition and in some coils no distinct steady state regime exists. The results showed that condensate mass depended dominantly on either gravitational or surface tension when comparing different coils under vertical and inclined orientations, but in general inclination reduced steady state retention by roughly 20%. In the high fin density heat exchangers, the surface tension effects played a dominant role in water retention. Heat exchangers geometry had a dramatic influence on water retention. For example, coils with rectangular fin arrangements and corrugated louver edges were

found to have about 50% lower retention compared to the same coils with triangular, straight edge louver fins.

### 2.3. Effect of surface materials

Surface wettability plays a key role on water retention and drainage of heat exchangers. In the industry, surface coating is a common method to enhance the retention and drainage performance. Min and Webb [27] focused on four different surface materials with the typical surface treatments including Aluminum (Al) and Copper (Cu). The authors designed one simple test facility to evaluate and observe the condensation process. The relationships of retention mass with Al surface contact angles under different conditions are measured as shown in Fig. 6. The results revealed that there existed one receding contact angle (40°) making the condensate retention per area maximum. When the receding contact angle is less than 40°, the condensate retention will increase with the increasing contact angle. Otherwise for the condition of receding contact angle larger than 40°, the condensate retention will decrease with the increasing contact angle. The author also implied that the ground fin surface can retain the least water mass on the surface because of its best wettability in the test materials.

Min et al. [28] tested three finned tube evaporators with different surface treatments used in residential air conditioning system including untreated Al, untreated Cu and hydrophilic treated Cu. The test results indicated that the surface-treating method was an effective means to improve the surface wettability for evaporators with Cu fin. The cooling capacity comparison results showed that the surface wettability had an unnoticeable effect on the total cooling capacity and the Cu fin evaporator had a 6% greater total cooling capacity than the Al fin evaporator.

Rahman and Jacobi [29] experimentally investigated the frost melt water flow behavior on microgrooved brass surfaces. It is an easier way for the draining of water condensate from the microgrooved surface that happens on the flat untreated surface.

### 2.4. Effect of long-term dry/wet conditions

Because of system controls and climate change effects, heat exchangers always are operated under long-playing wet/dry cycles.

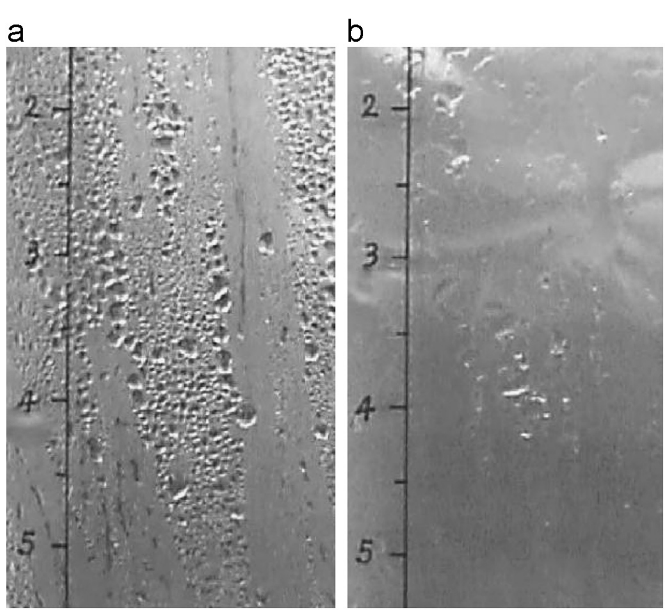


**Fig. 6.** Appearance of condensate formed on Al-AR (a, $\theta_R = 33°$) and as-received AQ surface (b, $\theta_R = 0°$) after 20 min [27].

The original surface wettability will show different performances under these conditions. Korte and Jacobi's experimental results showed that the surface wettability may increase during the first 100 h of wet–dry cycling and surface wettability effects on condensate retention may depend on fin spacing because the steady-state condensate retention was increased for the heat exchanger with 8FPI while decreased for the heat exchanger with 4 FPI [17]. Min et al. [30] experimentally investigated the long-term wetting characteristics of dehumidifying finned tube heat exchangers. The test samples were coated with different materials and oils. The uncoated coil showed a substantial decrease in both advancing and receding contact angles as the number of wet/dry cycles increased because of formation of a transparent Al oxide scale on the coil surface as well as the wet-to-dry pressure drop ratio. The effect of oil was observed on uncoated coils in the initial 100 cycles but disappeared after 500 cycles. The test results showed that the best coating maintained the wet/dry pressure drop ratio below 1.34 during all the cycles. The wet/dry pressure drop ratio could be correlated as a function of the receding contact angle but not as a function of the advancing contact angle.

Min and Webb [31] also studied the long-term wetting and corrosion characteristics of hot water treated Al and Cu fins. The cycle was a little similar with the previous tests [30]. During the tests, the advancing and receding contact angles and weights of the fin samples are measured as shown in Fig. 7(a). The test results suggested that the hot water soak was an effective means to improve the surface wettability of Al and Cu surfaces. The analysis results of the SEM photos and X-ray photoelectron spectroscopy examinations showed that the soaking operation and wet/dry cycling treatment did not result in significant material loss as shown in Fig. 7(b). Hong and Webb [32] conducted the similar tests for heat exchangers with different coating materials and the similar results were concluded. After a number of dry/wet cycles, the wettability of uncoated Al surface was obviously improved. This is because of surface oxidation and contamination during such cycles. Based on this understanding of the wettability mechanism, they suggested that a unidirectional grooved surface is used as an effective way to improve the wetting coating.

Kim et al. [33] experimentally compared heat exchangers fin wettability under wet conditions and long-term wet/dry cycles which were assembled with different fin surface hydrophilic treatment. One was treated by plasma gas and the other one was bare Al. The uncoated Al fin had 90° static contact angle at the initial condition and it decreased to 53° after 1000-cycles. The oxide scale formed on the Al surface was believed to have caused this result. But for the plasma coated Al fins, the static contact angle started at 22° and maintained very nearly the same value throughout the 1000 wet/dry cycles. The receding contact angle of the uncoated Al fin started at 45°, decreased with increasing number of cycles, and attained 6° after 1000 cycles. However, for the plasma coated fin, its initial and intermediate receding contact angle remained 0°. The test results showed that after 1000 wet/dry cycles, air side pressure drop of the plasma treated heat exchanger was 25% lower than that of untreated heat exchanger and it indicated that the plasma treatment provided long-term pressure drop reduction.

### 2.5. Droplets shape study

Depending on the wettability of the surface and heat exchanger geometries, condensation takes place in one of the three modes: filmwise, dropwise or mixed. Dropwise condensation will occur on a surface having poor wettability, while the filmwise condensation takes place on a surface having good wettability.

ElSherbini and Jacobi [34,35] experimentally studied the droplet shapes on fin surface. During the tests, contact angle, inclination

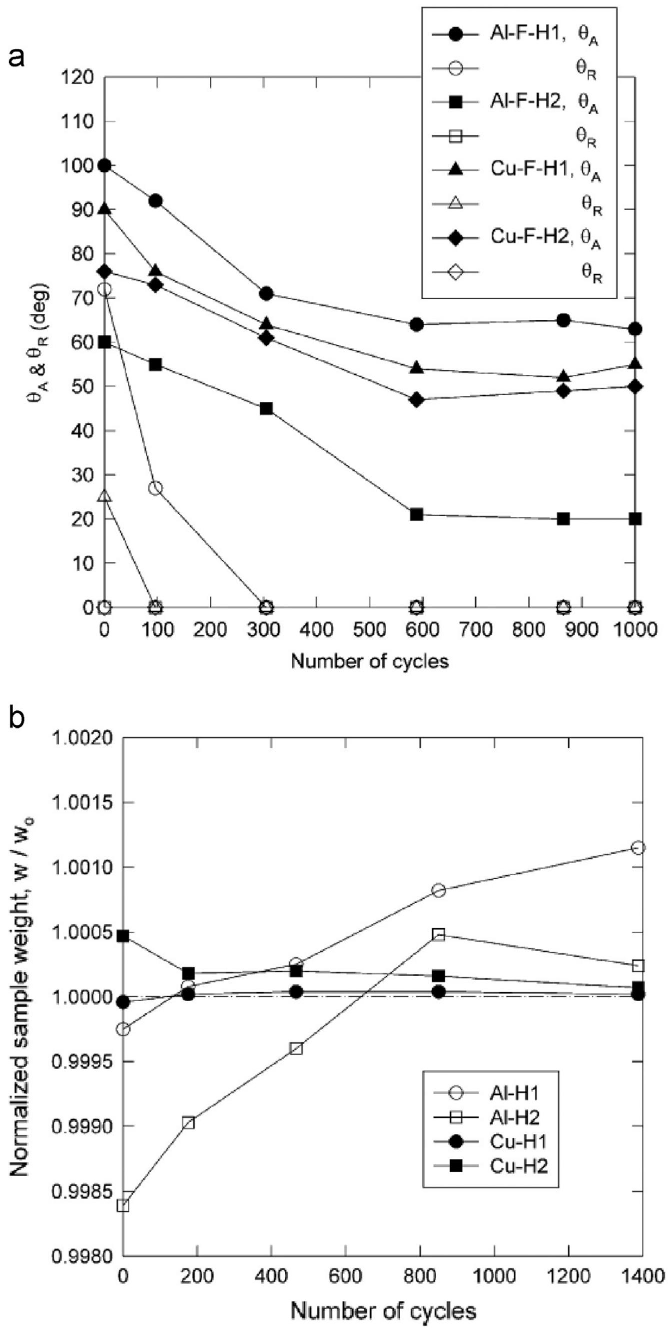


**Fig. 7.** Dependence of contact angles (a) and sample weight (b) of hot water soaked aluminum and copper fin samples on the number of wet/dry cycles [30].

angle, droplet shape and drop volume were measured. Eight engineering surfaces and two kinds of liquid which were water and ethylene glycol were tested. Fig. 8 shows the typical liquid droplet shape on a surface. The analyzed results showed that the maximum and minimum contact angles could accurately express contact angle as third-order polynomials of the azimuthal angle. The maximum contact angle was found to be approximately equal to the advancing angle. In the test, the authors also found that the general shape of a droplet contour is characterized as an ellipse. The profile of a droplet at a given azimuthal angle is approximated by two circles sharing a common tangent at the maximum height. Based on the test results, a new method was proposed to approximate the shapes of liquid droplets on vertical and inclined surface and the drop volume could be described as a function of the contact angles and three-phase contact line. This method could predict the

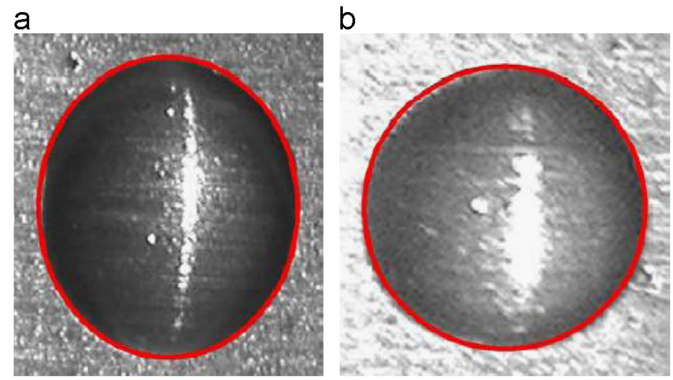


**Fig. 8.** Typical images of drop contours fit by (a) an ellipse and (b) a circle [33].

droplets volume correctly comparing with the test results and data from the other open literatures. They pointed out that the analysis of critical droplets based on the spherical-cap approximation resulted in up to a 75% error in maximum drop volume in some cases.

Yao et al. [36] observed the wettability on a hybrid surface consisting of hydrophobic and hydrophilic chemical materials and the results compared with the model by Kang and Jacobi [37]. They designed a very nice facility to test the droplet characteristics on hydrophobic and hydrophilic surface to understand the effects of wettability of hybrid surface. The contact angle changes on different types of hybrid surfaces showed that the hybrid surfaces have the potential to enhance droplet shedding in dropwise condensation.

Rahman and Jacobi [38] tested the wetting behavior and drainage of water condensate on microgrooved brass surfaces. The critical sliding angle for the microgrooved surfaces was found to be significantly smaller than for the base flat surfaces. The sliding angle showed a relationship with grooved geometry and was found to increase with pillar width and decrease with groove depth [39].

### 2.6. Experimental methods

In general, there are 3 different types of methods to observe the water retention and drainage behaviors in heat exchangers: wind tunnel, dynamic dip testing and air handling case test. The first one is mostly used in HVAC and refrigeration industry. It is characterized by precise and detailed measurements, but it is also an expensive method in time and cost. The second method is an easy and quick method developed in the recent ten years by some researchers [20,40,41]. The third one mainly focuses on water retention and drainage behaviors in the real units. According to the different research objectives, one available method will be selected.

#### 2.6.1. Wind tunnel

The wind tunnel test facility is widely used in heat transfer and heat exchangers studies. It consists of a closed-loop wind tunnel, a test section for testing heat exchangers exposed to horizontal air-flow and a coolant loop that circulates a single-phase coolant. It can be used to obtain measurements of retained condensate and heat transfer performance for various types of heat exchanger geometries. Fig. 9 shows the special test section designed for water retention and drainage studies [24]. The design allowed for both real-time and steady-state measurements of the mass of retained condensate. The test section was constructed using clear acrylic to allow for optical access which was insulated with thick polyethylene foam.

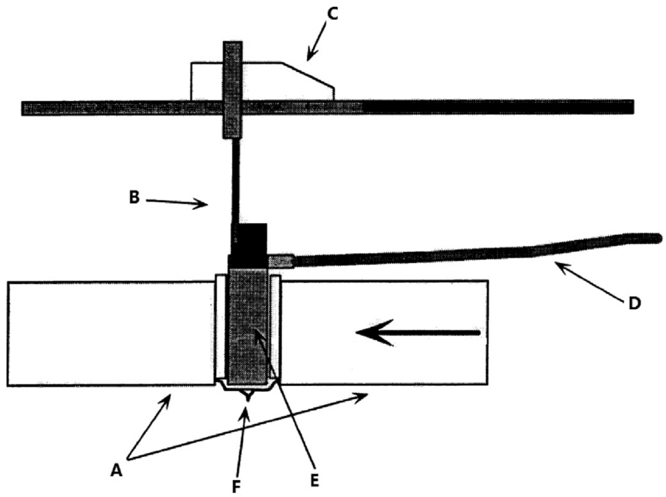


**Fig. 9.** Schematic of wind tunnel and real time retention measurement [24].

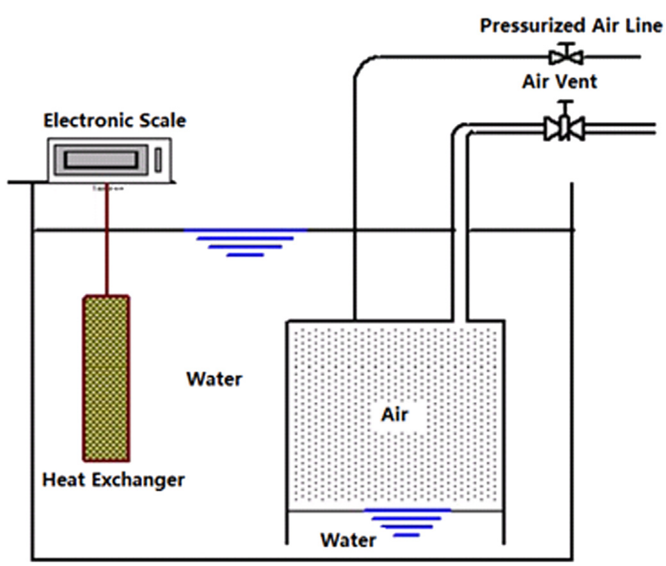


**Fig. 10.** Schematic of dynamic dip testing apparatus [20].

The balance needed to be zeroed prior to deposition of condensate but after the coolant pump and blower were operating. Once the entire system is running and the data acquisition program is started, mass measurements are recorded according to your setting recording frequency. The time at which the first condensate drips from the bottom of the coil is also recorded. After the amount of condensate retained on the coil reaches a steady value, the system is shut down.

The data acquisition system consisted of a control unit, programmable timer/counter and a personal computer. The measured data such as temperature, pressure, and flow rate would be recorded in a data text file for subsequent analysis.

*2.6.2. Dynamic dip testing*

The dynamic dip testing consists of a large water reservoir, a smaller submerged air reservoir to control the submersion of coils by displacement of water using compressed air, and a structure to suspend and weigh the heat exchanger as shown in Fig. 10 [20]. The heat exchanger is suspended from a balance using a fixed acrylic frame and simple mounting hardware. Before an experiment, the balance is turned on and zeroed after the test coil is suspended over the reservoir. At this point, the displacement tank is filled with water, and a final heat exchanger alignment check is performed. In order to initialize a test, the air vent is then closed, and the air supply is used to fill the displacement tank, causing the water level to rise and submerge the test specimen. Once the specimen is submerged, the air supply is closed. The water in the tank is agitated, and a fine brush is used to remove bubbles from the heat exchanger surface. While recording weight data, the air vent is suddenly opened to allow water into the displacement tank.

The simple procedures for the dynamic dip test are to submerge the test sample in the water, and measure the real-time water retention on the heat exchangers during water drainage.

Liu and Jacobi [22] evaluated the issues affecting the reliability of dynamic dip testing and the advantages and disadvantages of the wind tunnel method, dynamic dip testing and spaying method. They pointed out that the water droplet shape, water block bridges and factors affecting the condensation were different in these three method. It is suggested that the dynamic dip testing cannot provide an exact retention prediction but can work for a quick assessment purpose and this method is not suitable for round-and-fin tube with unusual wettability surface.

Compared to the wind-tunnel experiments, dip testing approach is simple, inexpensive, and relatively fast. And in wind tunnel, the formation of water condensate and mechanism can be studied. For the past 10 years it has been considered a highly reliable and valid method for assessing the condensate drainage behavior from the air-side surface of various designs of heat exchangers.

## 3. Water retention and drainage modeling

### *3.1. Mathematical model*

From the above analysis, it is concluded that the common research methods on water retention and drainage include two important steps. Firstly the fin surface wettability, water retention and drainage behaviors are studied by experiments. Secondly, based on the force balance and experimental observation, the numerical model will be proposed and validated by the previous test results.

In the open literatures, the main work on mathematical model of retention mass on heat exchangers was performed by A.M. Jacobi research group [2,18–20,41]. Based on the test results, the condensation mass prediction model was established by Korte and Jacobi where heat exchanger geometry, advancing and receding contact angles and air-side Reynolds number were taken into account [2]. The approach was based on the basic assumptions that the fins spacing is too far apart for bridges formation and there are only droplets on the heat exchanger fin surfaces. This new model was successful in predicting the magnitude and trends of condensate retention for plain-fin-and-tube heat exchangers with fin spacing much larger than the height of retained droplets. There are some main shortcomings of this model such as its use of droplet size distribution data from one location on a fin, not recognizing the effects of condensate sweeping on large fins and the potential effect of heat flux on droplet-size distributions. The model also did not consider the complex flow development and edge effects in the heat exchanger. Furthermore, extensions of the plain-fin model to the complex, interrupted-fin geometry often used in air-cooling are desired. Korte and Jacobi [17] have proposed modifications to account for inter-fin coupling, and work in this direction is continuing. Yin and Jacobi [19], and Kim and Jacobi [41] have proposed modifications to include surface-interruption effects, which may allow modeling of slit-fin or

louvered-fin heat exchangers. Another important extension to this approach is to consider heat exchangers with a horizontal airflow, rather than the down-flow configuration studied in this model.

Mathur [42] proposed a water droplet carryover model as a function of evaporator coil size, water droplet diameters and face velocity. The simulated data had a good agreement with the experimental data. The developed model could be used to calculate the maximum horizontal distances with the airstream for a range of water droplet diameter. This model can help the heat exchanger designer better understand the characteristics of condensate carryover and serve as reference material for design of the condensate catching pan.

ElSherbini and Jacobi [43,44] proposed a precious condensate retention mass model based on droplet volumes, contact angles, maximum diameters and retentive forces for plain-fin heat exchangers. They indicated that the model was only applicable for the advancing contact angles from 45° to 120°. This model successfully predicted the condensate retention results measured by other independent researchers. The critical fin spacing to avoid bridges formation was also calculated from droplet geometry and the obtained results agreed with the experimental results from the author's group very well.

Young–Laplace equation can be used to govern the shape of the liquid–vapor interface. By numerically solving this equation, Xia et al. [40] proposed a model to predict the shapes of a droplet or condensate bridge. The model was successful in predicting the shapes and volumes of condensate elements on surfaces with widely various hydrophilicity. The model also could be used to analyze the effect of hydrophilicity on inter-fin or inter-louver condensate bridges. In Jacobi's group, the hydrophilic and super-hydrophilic surfaces were experimented to improve the heat exchanger drainage behaviors [45,46].

Xu et al. [47] proposed a method to describe the steady-state condensation based on the force balance on retained condensate. The influences of air dry-bulb temperature, air humidity and Reynolds number on condensate retention were discussed. The comparison with experimental results showed that the new model was successful in predicting the general trend of condensate retention. But a main shortcoming of the model is that the effect of geometrical complexity on condensate retention is not included and also the model neglects the edge effects of a cooling coil.

According to the observation results on hybrid surfaces, Yao et al. [36] proposed a numerical model based on energy minimization to predict the contact angles on hybrid surfaces. The numerical results can agree well with the experimental data. Based on conservation equations and the free-energy minimization theory, Kang and Jacobi [37] proposed a theoretical model to predict the contact angle on a rough surface. The simulation results agreed very well with the existing experimental data and had a higher precision than that of the classical models.

Sommers [48] also established a numerical model for predicting liquid droplet volume on microgrooved surfaces with various geometries. The experimental comparison showed that this model can calculate the actual droplet volume for 88% data within 10%.

### 3.2. Computational fluid dynamics (CFD) simulation

With the development of high performance computers, computational fluid dynamics have been widely used in heat transfer and fluid flow research including in air side performance of heat exchangers. Many researchers focused on the heat transfer and frictional characteristics of CFD simulation for various types of fins and heat exchangers under dry conditions.

A lot of research has been carried out in the numerical simulation of heat and mass transfer in tube-and-fin heat exchangers under dehumidification conditions by Comini [49–56]. He used finite-element approach to deal with both conduction and convection occurring simultaneously. He argued that in principle, the modeling of conduction and convection processes that involve adjacent fluid and solid domains requires the solution of a coupled problem. However, conduction in the solid and convection in the fluid can often be decoupled by imposing constant temperature boundary conditions on the interface between the fluid and solid domains. The most important assumption made in his modeling was that the condensate is promptly removed from the wall once it formed. There were two reasons to justify this assumption. Firstly, designers always devote much effort to the achievement of a good drainage since retained condensate might either blow-off the heat exchanger, creating an unwanted fog, or remain on the cooling surface, providing a medium for the growth of bacteria. Secondly, the influence of liquid droplets and films has not even been fully established experimentally. So they cannot be easily accounted for in the model. The prevailing opinion was that the pressure loss is increased by the condensate at least in the film mode but it is still unclear whether the heat transfer coefficient will increase or decrease.

So it is still an open question concerning the modeling of condensation process about whether it is dropwise or filmwise or even mixed type. According to experimental observations, filmwise condensation rarely occurs in industrial finned tube exchangers. But the drainage of condensate can easily lead to the formation of liquid films.

Other researcher like Yang and Sekhar [57] also did a CFD modeling for a compartmentalized cooling coil under dehumidifying conditions. They also disregarded the film condensation by assuming prompt removal of condensate from the exchange surface. User Defined Function (UDF) method is coupled to the coil model which is created on the software platform. In the UDF, condensation is assumed to take place if the wall temperature is less than or equal to the saturation temperature corresponding to the partial pressure of water vapor at the surface. In this case, the multiphase model could be simplified to a multispecies model. Condensation appearing only at the zones adjacent to the interface of moist air and tube or fin wall was another assumption.

Volchkov et al. [58] did a numerical study of boundary-layer transfer processes with surface steam condensation from humid air and determination of the domain where the triple Reynolds analogy for these conditions holds. Asbik et al. [59] performed a numerical study on the laminar film condensation of pure saturated vapor flowing in the direction of gravity on a single horizontal elliptic cylinder or a bank of elliptical tubes. The equality of shear stress at the liquid–vapor interface was used as the coupling condition between the two phases. He assumed that the vapor velocity field was not affected by the condensate flow from one elliptic cylinder to another. Further, the condensate flow as a sheet was valid only for very high condensation rates. At low condensation rates, because of surface tension forces, the condensate may flow as droplets or as columns. Louahlia-Gualous and Omari [60] also provided numerical analysis of the evaporation heat transfer of a falling liquid film on a horizontal cylinder.

Other than condensation in fin-and-tube heat exchanger surfaces, a lot of researches have been accomplished in different places. Zhang and Faghri [61] simulated the condensate at the liquid–vapor meniscus in a capillary grooved structure which assumes zero gravity, laminar flow and constant fluid properties. Condensation on the fin top and meniscus was modeled by using appropriate source terms in continuity Volume of Fluid (VOF) model and energy equations. The VOF appeared to be a good studying candidate because it can be used to determine the location of the interface.

Liu et al. [62] developed a 3-D transient CFD model to simulate the condensation in a test chamber. It was claimed that for when

to determine whether and when condensation occurred, it became a transient heat and mass transfer problem. The unsteady-state simulation method was more useful than a steady-state one. The simulation revealed the process of condensation in the chamber. At first, it happened in the corner near the ceiling and then expanded along the ceiling and the vertical walls. It was used to design the inlet and outlet of ventilation to avoid condensation on walls.

## 4. Conclusions

Water retention and drainage behaviors have great influence on heat exchanger performance under dehumidifying conditions. Numerous experiments have been carried out on the effects of fin materials, heat exchanger geometries, heat exchanger installations, air side conditions and wet/dry conditions on droplets shapes, hydraulic–thermal performance and water retention and drainage behaviors. The general conclusions have been drawn as follows.

Depending on the wettability of the surface and heat exchanger geometries, condensation takes place in one of the three modes: filmwise, dropwise or mixed. Dropwise condensation will occur on a surface having poor wettability, while the filmwise condensation takes place on a surface having good wettability.

The detailed geometries of heat exchangers and fin surface coating play the key roles in water retention and drainage behaviors, but there are no general conclusions on these factors. For example, the enhanced surface wettability helps reduce retention for flat-tube heat exchangers, but increases water retention on round-tube heat exchangers, because drainage in flat-tube heat exchangers is geometrically restricted, while in round-tube heat exchangers it is wettability dominated.

Some new measurement methods have been developed for condensate retention and behavior study. Although these methods are easy and quick, they should be carefully selected under some special test conditions and test samples. The wind tunnel is still the best equipment to observe water retention and drainage behaviors on heat exchangers although this method is expensive and time consuming.

Based on the observations, test results and forces balance analysis, many mathematical models are proposed to predict the contact angles, droplet shapes on fin surface and water retention mass on heat exchangers. These models successfully predict the magnitude and trend of droplets volume and water retention mass. There are some factors that have not been considered in these models and the generality of these models is not sufficient. Although there are numerous publications based on droplets shapes, there is no open literature on water retention models based on filmwise condensation on air side of heat exchangers.

In general, CFD has been used to perform numerical simulations of heat and mass transfer in tube-and-fin heat exchangers under dehumidifying conditions on the assumption that the condensate is promptly removed from the fin surface once it is formed. Other than this, no research has been found about the numerical study of droplet or film formation and flowing on the fin surface. So it is a new challenging problem concerning CFD simulation of droplet and film flowing on fin surface and its effect on heat transfer and pressure drop performance of various fin types.

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